

Multi-Strangeness Production in Hadron Induced Reactions

T. Gaitanos¹, Ch. Moustakidis¹, G.A. Lalazissis¹, H. Lenske^{2,3}

¹ *Dept. of Physics, Aristotle University of Thessaloniki, 55124 Thessaloniki, Greece*

² *Institut für Theoretische Physik, Universität Giessen, D-35392 Giessen, Germany*

³ *GSI Helmholtzzentrum für Schwerionenforschung, D-64291 Darmstadt, Germany*

email: tgaitano@auth.gr

Abstract

We discuss in detail the formation and propagation of multi-strangeness particles in reactions induced by hadron beams relevant for the forthcoming experiments at FAIR. We focus the discussion on the production of the decuplet-particle Ω and study for the first time the production and propagation mechanism of this heavy hyperon inside hadronic environments. The transport calculations show the possibility of Ω -production in the forthcoming $\bar{\text{P}}\text{ANDA}$ -experiment, which can be achieved with measurable probabilities using high-energy secondary Ξ -beams. We predict cross sections for Ω -production. The theoretical results are important in understanding the hyperon-nucleon and, in particular, the hyperon-hyperon interactions also in the high-strangeness sector. We emphasize the importance of our studies for the research plans at FAIR.

Keywords: $\bar{\text{P}}\text{ANDA}$, \bar{p} -induced reactions, Ξ -induced reactions, double- Λ hypernuclei, Ξ -hypernuclei, ΞN interactions, Ω -baryon, Ω -production.

1. Introduction

Hadronic reactions induced by heavy-ion and hadron beams build the central tool to look deeper inside the hadronic equation of state (EoS). Of particular interest is the strangeness sector of the EoS. Baryons with strangeness degree of freedom modify the nuclear EoS significantly at compressions beyond saturation [1, 2, 3, 4]. Such effects show up already in ordinary matter (finite nuclei). Adding hyperons to a nucleus typically leads to a rearrangement of the whole system. Although hyperons are fermions, they do not underly the Pauli-exclusion principle with nucleons because strangeness makes them distinguishable. As a consequence one observes increased binding energies and even a slight shrinking of hypernuclei, corresponding to a larger saturation density [5].

Hyperons are also important for nuclear astrophysics. It is well known that the presence of hyperons in the cores of neutron stars may play important role in determining both bulk properties of neutron stars as well as various dynamical processes [6, 7, 8]. In particular, hyperons can be formed in the interior of neutron stars when the in-medium nucleon chemical potential is large enough to make the conversion of a nucleon into a hyperon energetically favorable. Actually,

they can appear at densities of about 2 – 3 times the saturation density of nuclear matter. This conversion relieves the Fermi pressure exerted by the nucleons and makes the equation of state softer. It has been found that, the mentioned softness of the equation of state, leads to low values of maximum neutron star mass. This is in contradiction with a very recent accurate measurements of the masses, $M = 1.97 \pm 0.04 M_\odot$ (PSR J1614-2230 [9]) and $M = 2.01 \pm 0.04 M_\odot$ (PSR J0348+0432 [10]). This is the so called hyperon puzzle where while the presence of hyperons at high densities is predicted by the nuclear theory is not compatible with measured neutron star masses.

There are, mainly, three different approaches to study the hyperon formation in neutron star matter. The first one is based in the framework of the Brueckner-Hartree-Fock approach by using realistic nucleon-nucleon and hyperon-hyperon interactions [11, 12, 13]. The second method is based on Relativistic Mean Field Theory [14, 15] and the third one on the construction of an effective equation of state by employing Skyrme-type interactions [16]. It has been suggested that the hyperon-hyperon repulsion and hyperonic three-body interactions effects may help to solve the hyperon puzzle problem [11]. Another recent review article on this still debated issue can be found in Ref. [17] (and further references therein).

The hyperon-puzzle is one of the most recent issues concerning the study of the static and dynamic properties of the neutron stars [17, 18, 19]. The solution of this problem may lead to a much better understanding of a complex phenomena in neutron star interior, such as the hyperon superfluidity and the hyperon bulk viscosity. All the mentioned effects are directly related with the neutron star cooling process, the glitches and the radiation of gravitation waves [20, 21, 22, 23, 24].

Heavy-ion collisions at intermediate relativistic energies of several GeV per particle supply information on the in-medium hadronic properties over a broad range in baryon density [25, 26]. Heavy-ion reactions at energies around the strangeness production threshold have been studied theoretically and experimentally in the past [27, 28]. One of the most important achievements was the conclusion of a soft nuclear EoS at densities $\rho_B \simeq (2 - 3)\rho_{sat}$, as a result from collective flow [25] and kaon production [27, 29, 30, 31] studies. For further reading concerning the high density equation of state of symmetric matter and the symmetry energy of compressed matter we refer to Refs. [32, 33, 34]. Supplementary information on the in-medium properties of kaons have been reported also in Ref. [35]. Further investigations on strangeness and hypernuclear production in hadronic reactions have been recently started by several theoretical and experimental groups [36, 37, 38, 39].

While intermediate-energy heavy-ion reactions give essential details of the highly compressed matter, the high production thresholds of heavier hyperons hinder their production. On the other hand, the main task of flavor nuclear physics consists in the construction of the in-medium interaction between the octet and decuplet baryons N , Λ , Σ , Ξ and Ω [40, 41, 42, 43, 44]. A possible way to overcome the high production thresholds without going beyond the nucleonic environment (quarks) is to study hadron-induced reactions. Of particular interest are antiproton-beams because of their high annihilation cross sections at intermediate energies [45]. Antinucleon-nucleon annihilation into multiple meson production and hyperonic resonances are the most important channels. Strangeness mesons (antikaons) and resonances can accumulate energy and strangeness degree through secondary scattering and produce by multi-step processes heavier

hyperons.

Up to now little is known about the hyperon-nucleon interaction. The uncertainty increases as the strangeness degree of freedom grows. Experimental information on the free hyperon-nucleon interactions is accessible in the $S=-1$ sector (ΛN and ΣN channels) [46, 47, 48, 49, 50], but already for the $S=-2$ channels involving the cascade hyperon the situation is still very sparse [51]. Concerning the $S = -3$ -processes with the Ω -baryon no experimental data still exist. Consequently, from the theoretical side the parameters of the bare YN-interactions in the $S = -1$ channel (ΛN , ΣN) are better under control than those parameters in the $S = -2$ sector (ΞN , $\Lambda\Lambda$, $\Lambda\Sigma$). Indeed, various theoretical approaches with similar results for the $S = 0$ channel (NN -interaction) predict quite different results for the bare ΞN -channels [49, 51].

We have investigated in the past the formation and production mechanisms of hyperons [52], fragments [53] and hyperfragments [54, 55] in reactions induced by heavy-ions, protons and antiprotons. Recently the role of the multi-strangeness hyperon-nucleon interaction ($S = -2$) has been explored in detail [56]. It turned out that different hyperon-nucleon interaction models lead to observable effects and may constrain the high strangeness YN and YY interactions at $\overline{\text{PANDA}}$. In this work we extend our previous studies by considering the possibility of Ω -production. The Ω -baryon consists of three strange quarks preventing abundant Ω -production in antiproton induced reactions. However, secondary strangeness exchange processes can increase the production of this heavy baryon. After an introduction to the theoretical aspects in Sec. 2 we discuss possible reaction mechanisms for Ω -production in primary and secondary chance binary collisions (Sec. 3). In Sec. 4 we present the results for reactions involved in the $\overline{\text{PANDA}}$ -experiment [57, 58]. That is, antiproton-induced reactions including the supplementary step with secondary Ξ -beams. We conclude the possibility of Ω -formation in the reactions with the secondary beam at high energies above the Ω -production threshold.

2. Hyperon-nucleon interactions

In this Section we briefly outline the current status of the $S = -1$ and $S = -2$ in-medium octet-interactions before discussing the relevant part of the Ω -baryon production. That is, the octet- and decuplet-interactions in the $S = -3$ sector.

2.1. Hyperon-nucleon interaction in the $S = -1$ sector

The hyperon-nucleon interaction is not yet fully understood for the entire baryon octet and decuplet. However, it is better fixed in the $S=-1$ sector from studies on single- Λ hypernuclei [59, 60, 61, 62, 63, 64, 65, 66, 67, 68] and from Λ (and Σ) production in reactions induced by hadrons and heavy-ions [54, 69, 70, 71]. The free hyperon-nucleon interaction in the $S=-1$ channels has been investigated in detail within one-boson-exchange (OBE) approaches [72, 73, 74]. The rare available experimental data allowed to fix the various cross sections for a variety of elementary channels [72, 75]. In-medium scattering has been also performed within the same OBE-scheme and in the spirit of relativistic mean-field (RMF) and density dependent hadronic (DDH) approaches [76]. The parameters are determined by simultaneous fits to NN- and YN-scattering observables in the $S=-1$ sector. While in the $S=0$ sector (NN-interactions) there are about 4300 scattering data of high quality available, in the $S=-1$ YN-part only 38 scattering data

are accessible. They still allow a reasonable determination of the ΛN and ΣN model parameters. Thus, despite of model differences all the theoretical approaches yield similar predictions for, e.g., potential depths and scattering cross sections for exclusive channels between nucleons and Λ -hyperons. Remaining uncertainties for $S=-1$ interactions are related to the unsatisfactory experimental data base.

The basic task of determining the full set of YN and YY hyperon interactions is still far from being under control to a satisfactory degree of accuracy. The progress made in the last decade or so for $S = -1$ systems is only part of the full picture since this involves mainly single- Λ hypernuclei, supplementing the few data points from old $p\Lambda$ and $p\Sigma$ experiments, e.g. in [77, 78, 79]. The latter are essential input for the approaches developed over the years by several groups. While the Nijmegen [72, 73] and the Juelich group [74], respectively, are using a baryon-meson approach, the Kyoto-Niigata group [47] favors a quark-meson picture, finally ending also in meson-exchange interactions. However, none of the existing parameter sets is in any sense constrained with respect to interactions in the $|S| \geq 2$ channels.

Furthermore we emphasize the theoretical developments based on lattice QCD simulations [80] and on the chiral effective field (EFT) theory [81]. Within the chiral EFT power counting prescriptions are employed to the YN -interactions [82, 83]. The chiral EFT approach has been recently applied to $Y(S = -1)N$ -interactions in symmetric and asymmetric nuclear matter [84]. Chiral EFT predictions for the real and imaginary parts of the in-medium optical Λ - and Σ -potentials are discussed. According to these studies, the in-medium Λ -potential is attractive while the corresponding Σ -potential is repulsive for single-particle momenta close to the Fermi-momentum.

2.2. Hyperon-nucleon interaction in the $S = -2$ sector

Concerning the $S=-2$ sector only theoretical predictions exist so far in the literature. Among others, the chiral-unitary approach of Sasaki, Oset and Vacas [50] and the effective field theoretical models of the Bochum/Jülich groups [50] are representative examples. In this context we also mention the chiral effective field-theoretical approaches. They have been further extended to the YN -interactions in the $S = -2$ sector [85, 86] with predictive power on $\Lambda\Lambda$ and ΞN cross sections. The Nijmegen [49] models are based on the well-known OBE picture to the NN -interaction, in which one then embeds the strangeness sector with the help of $SU(3)$ symmetry. Fujiwara et al. [87] have developed quark-cluster models for the baryon-baryon (BB) interactions in the $S=0,-1,-2,-3,-4$ sectors. Note that chiral EFT gives predictions on strangeness exchange cross sections such as $Y(S = -1)\Xi$ and $\Xi\Xi$ cross sections, see Refs. [85]. In the $S=-2$ sector involving the cascade-particles (Ξ), the uncertainties and, therefore, the discrepancies between the models are considerably larger [51]. We have investigated this task in a recent work [56] by choosing two particular model calculations for the hyperon-nucleon in-medium interaction in the $S=-2$ sector. For instance, the one-boson-exchange calculations of the Nijmegen group in the extended soft-core version ESC04 of 2004 [49] and the quark-cluster approach [87] give very similar predictions for the nucleon-nucleon interaction, but differ considerably between each other in the ΞN -interactions. As discussed in detail in Ref. [56], observable signals arise in reactions induced by Ξ -beams on intermediate mass target nuclei. These signals show up in

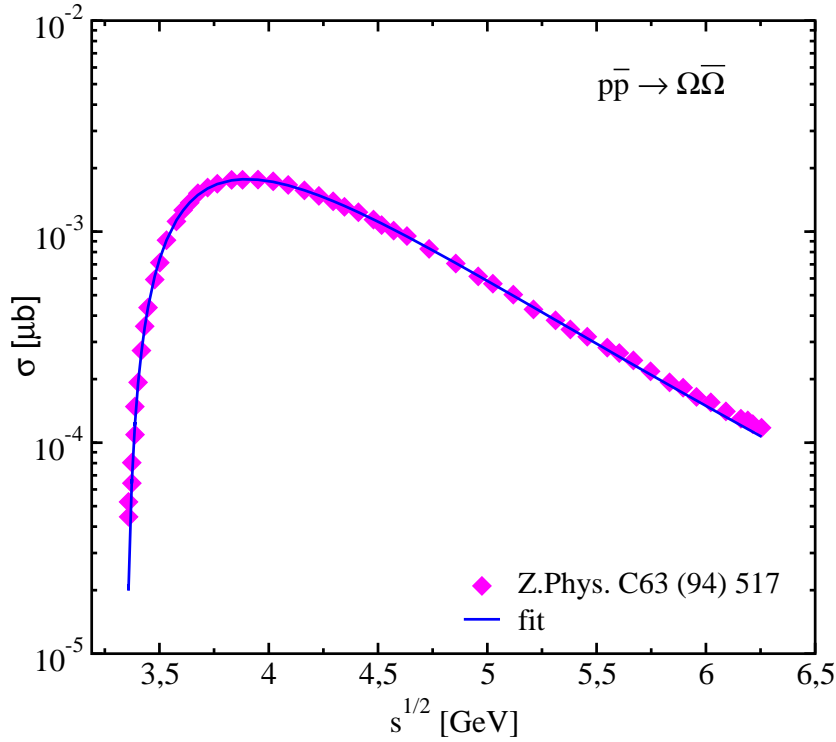


Figure 1: Antiproton-proton cross section for Ω -baryon production. The symbols refer to theoretical estimations from Ref. [88] and the solid curve is a parametrization used in the transport calculations.

the amount of bound cascade hyperons inside the target and, in particular, in the production of double-strangeness hypernuclei.

2.3. Hyperon-nucleon interaction in the $S = -3$ sector

In the higher strangeness sector $S = -3$ the situation is still not understood. For reasons which will become clear below, we distinguish between primary and secondary production processes of the Ω -baryon. For the primary binary processes we focus the discussion to antiproton-proton collisions. Various possibilities exist for the secondary Ω -baryon production, which will be discussed below.

For antiproton-proton annihilation into Ω particles one theoretical work exists in the literature only [88], which is based on reggeon-like calculations for rather low energies of interest. The estimations of these calculations are shown in Fig. 1 in terms of the total production cross section (symbols). The solid curve is a polynomial parametrization to the theoretical results, which will be used in the transport descriptions. At first, one can see that the Ω -production cross section is very low. Above the production threshold of $\sqrt{s} \geq 3.344$ GeV (corresponding to a kinetic energy of $E_{lab} = 4$ GeV or to a beam momentum of $p_{lab} = 4.9$ GeV in the laboratory frame) the cross section grows up to a maximum of several nb only before starting to decrease again. Note that these scales are approximately one (two) order of magnitude less with respect to the antiproton-proton production cross section of the cascade (Λ) particles, as shown and discussed in Ref. [88].

One can naively explain the low production probability of the Ω particles, without going into theoretical details. In contrary to the Λ and also the cascade hyperons, the decuplet Ω -particle consists uniquely of three strange quarks. These have to be generated in intermediate flavor exchange processes during the antiproton-proton annihilation. Also the heavy Ω -mass further reduces the phase-space with respect to the corresponding Λ and Ξ phase-space factors. Thus,

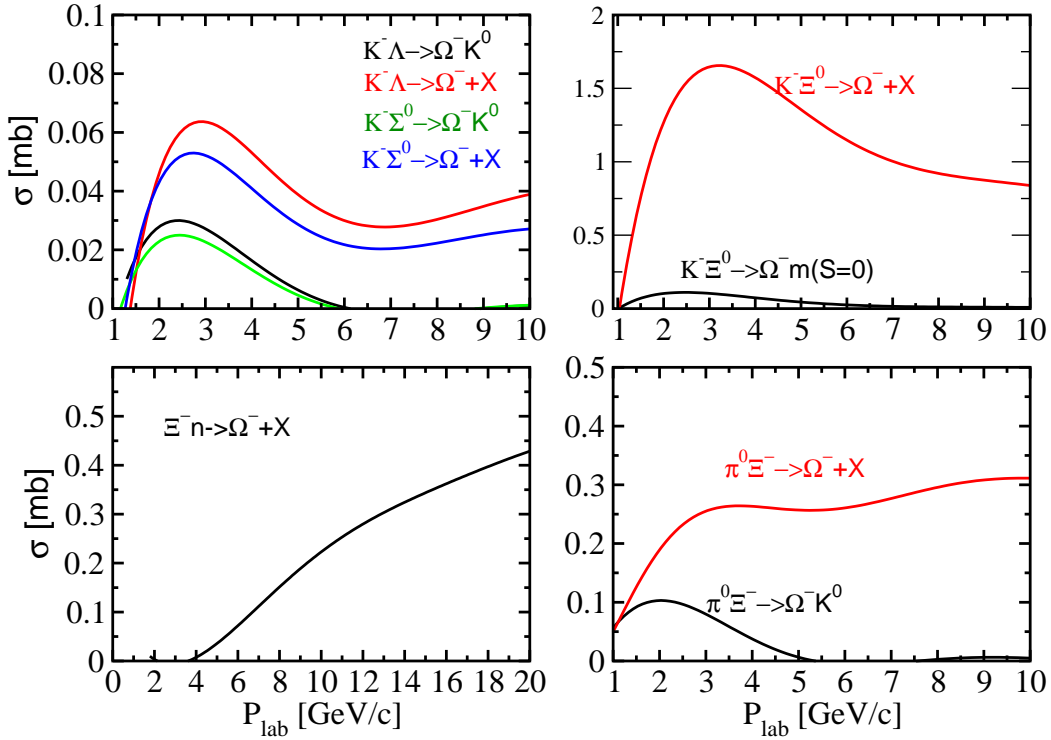


Figure 2: Total cross sections for various channels (as indicated) for Ω -baryon production.

the Ω -production cross section becomes significantly lower.

Consequently, the question arises whether the production of heavy hyperons with multi-strangeness degree of freedom is possible in the energy domain planned at FAIR. In this context one should remind, that the $\overline{\text{PANDA}}$ -experiment consists of a two-step process: Antiproton-beams on a nuclear target as the origin of cascade particles (Ξ^-), which will serve as a Ξ^- -beam for collisions with a secondary target. Thus, secondary re-scattering may contribute to Ω -production as well. Fig. 2 shows the cross sections for some particular secondary processes. Obviously we select such processes with the highest strangeness degree of freedom in the initial channel. That is, re-scattering between antikaons and other hyperons with $S = -1$ (panels on top in Fig. 2) or between the cascade particles with other non-strange baryons or mesons (panels on the bottom in Fig. 2). In principle, these cross sections can be evaluated within chiral EFT approaches. However, in view of the limited energy range accessible in the EFT approach and the persisting sizeable bands of uncertainty, in the present study we prefer to use phenomenological cross sections extracted directly from elementary events by means of the PYTHIA program [89]. At first, the particle energies should lie above the corresponding Ω -production thresholds. With the Ω -mass of 1.672 GeV this results to a threshold of $\sqrt{s} \geq 3.107$ GeV for the $\Xi N \rightarrow \Omega K N$ -channel (corresponding to $E_{lab} \geq 3.75$ GeV kinetic energy or to $p_{lab} \geq 3.5$ GeV beam momentum). According to these calculations high energy Ξ -beams are necessary to enforce the formation of Ω -baryons from second chance binary collisions, as shown in the bottom-left panel of Fig. 2. Note that the order of magnitude of these cross sections (mb-region) is comparable with the typical strangeness production cross sections ($NN \rightarrow NYK$ and $\pi N \rightarrow YK$ with $Y = \Lambda, \Sigma$ and K for the hyperons and kaons, respectively). Furthermore the Ω -production cross sections for primary $p\bar{p} \rightarrow \Omega\bar{\Omega}$ -channels is several orders of magnitude less with respect to the re-scattering cross sections. Obviously, high energy Ξ -beams with rather heavy-mass nuclear

targets might be necessary to produce Ω -particles with high probability. This is the topic of the next section.

3. Hadron-induced reactions

For the theoretical realization of hadron-induced reactions we use the widely established relativistic Boltzmann-Uheling-Uhlenbeck (BUU) transport approach [90]. The kinetic equations are performed numerically within the Giessen-BUU (GiBUU) transport model [91]. The GiBUU equation is given by

$$\left[k^{*\mu} \partial_\mu^x + (k_\nu^* F^{\mu\nu} + m^* \partial_x^\mu m^*) \partial_\mu^{k^*} \right] f(x, k^*) = \mathcal{I}_{coll}. \quad (1)$$

It describes the dynamical evolution of the 1-body phase-space distribution function $f(x, k^*)$ for the various hadrons under the influence of a hadronic mean-field (l.h.s. of Eq. (1)) and binary collisions (r.h.s. of Eq. (1)). For the mean-field we adopt the relativistic mean-field approximation of Quantum-Hadrodynamics [92]. The hadronic potential shows up in the transport equation through the kinetic 4-momenta $k^{*\mu} = k^\mu - \Sigma^\mu$ and effective (Dirac) masses $m^* = M - \Sigma_s$. The in-medium self-energies, $\Sigma^\mu = g_\omega \omega^\mu + \tau_3 g_\rho \rho_3^\mu$ and $\Sigma_s = g_\sigma \sigma$, describe the in-medium interaction of nucleons ($\tau_3 = \pm 1$ for protons and neutrons, respectively). The isoscalar, scalar σ , the isoscalar, vector ω^μ and the third isospin-component of the isovector, vector meson field ρ_3^μ are extracted from the standard Lagrangian equations of motion [92]. For the model parameters (obvious meson-nucleon couplings) we use the $NL3$ -parametrization, which includes non-linear self-interactions of the σ field [93]. The meson-hyperon couplings at the mean-field level are obtained from the nucleonic sector using simple quark-counting arguments. The in-medium nucleon-, Λ -, Σ - and Ξ -potentials are $U_N = -46$, $U_\Lambda = -38$, $U_\Sigma = -39$ and $U_\Xi = -22$ (in units of MeV), respectively, at saturation density and zero kinetic energy [52]. For the Ω -mean field one could use again the quark-counting argument. However, as we will see below, directly produced heavy baryons like the Ω escape immediately from the nuclear environment, thus inhibiting the formation of bound states. Important for captured Ω -particles inside nuclear matter will be secondary scattering processes. For the in-medium potential of the Ω -baryon we use here the same potential as that for the nucleons for simplicity. The collision term includes all necessary binary processes for (anti)baryon-(anti)baryon, meson-baryon and meson-meson scattering and annihilation [91]. For more details of the corresponding mean-field and cross section parameters we refer to Refs. [52, 46, 50, 94, 95]. Relevant for the present work is the implementation of the new parametrizations for the $N\bar{N} \rightarrow \Omega\bar{\Omega}$ -scattering, as discussed in the previous section. Having the cross sections for all exclusive elementary channels of interest, the collision integral of the transport equation is then modelled within conventional Monte Carlo methods.

We have performed transport calculations for antiproton-induced reactions including the second-step process of Ξ^- -collisions on a secondary nuclear target. We have used two different target nuclei, ^{93}Nb and ^{64}Cu for the \bar{p} - and Ξ -induced reactions, respectively. For the antiproton-nucleus reactions a heavier target is used to increase the rare Ω -production via secondary scattering, while in the Ξ -induced reactions a lighter target is sufficient for the same purpose. In extension to our previous work high energy secondary cascade-beam are considered

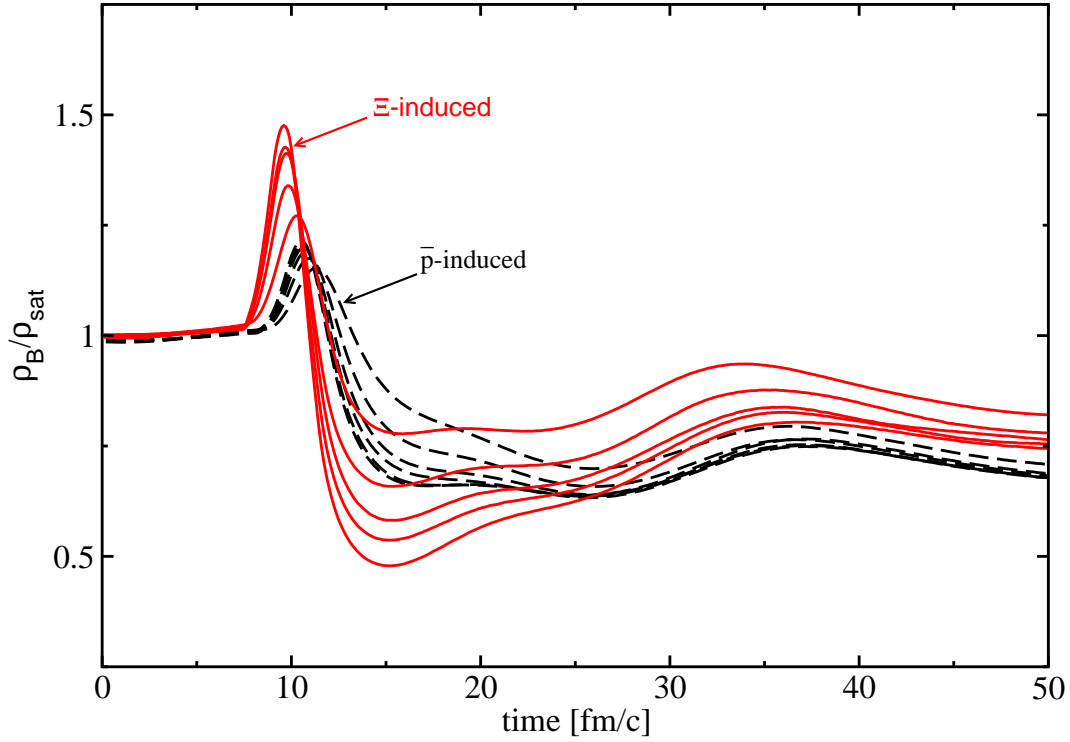


Figure 3: Baryon density ρ_B (in units of the saturation density ρ_{sat}) at the origin of the target nucleus as function of time for $\bar{p} + {}^{93}\text{Nb}$ and $\Xi^- + {}^{64}\text{Cu}$ reactions, as indicated.

here. Before analyzing the production of particles of interest, we discuss the density regions tested in such reactions. This is shown in Fig. 3 in terms of the temporal evolution of the baryon density for antiproton- and Ξ -induced reactions at different beam energies. The density is calculated at the origin of the corresponding nuclear target. Note that the compressions of the matter is less pronounced in \bar{p} -induced reactions with respect to the Ξ -nucleus collisions. This result seems surprising, since the in-medium antibaryon is very attractive in RMF, as discussed in Ref. [96]. Also note that a heavier nucleus is used in the \bar{p} -induced reactions. However, the imaginary part of the in-medium antiproton optical potential is rather strong [96, 97]. It causes immediate annihilation already at the nuclear surface before deeper penetration of the antiproton. Consequently, the density averaged over the events does not differ much from the saturation value. Furthermore, apart the trivial time shifts between the various beam energies, both types of reactions show a similar behavior of the density evolution. During the hadron (\bar{p} , Ξ) penetration into the nucleus binary processes cause a moderate compression at the center of the target. In the subsequent de-excitation stage the central baryon density decreases due to particle emission. In such reactions densities close to saturation $0.5\rho_{sat} \leq \rho \leq 1.5\rho_{sat}$ are achieved and, thus, one can probe the in-medium interactions in this density range.

Fig. 4 shows the results of the transport calculations in terms of rapidity spectra of various produced hyperons for \bar{p} -induced reactions at different beam energies. We observe an abundant production of the lightest hyperon (Λ) with a broad spectral distribution in longitudinal momentum followed by the production of the cascade particles. The big differences in their production yields arise from the smaller annihilation cross section into cascade particles relative to that into the $\Lambda\bar{\Lambda}$ -channel. Note that here secondary re-scattering is mainly responsible for the breadth of the rapidity spectra. It causes the capture of these hyperons inside the target nucleus (Λ_{bound} and Ξ_{bound} rapidity yields) with the subsequential formation of Λ -hypernuclei. We do not go into further details concerning the formation of hypernuclei. This task has been studied in the past in

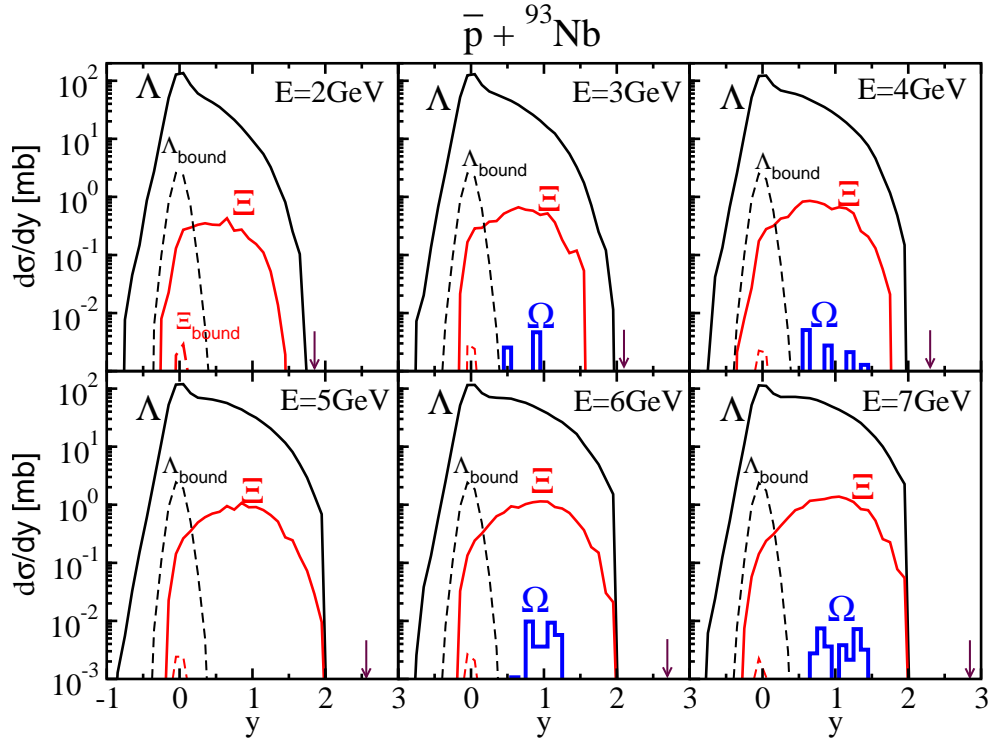


Figure 4: Rapidity distributions for various hyperons (as indicated) produced in $\bar{p} + {}^{93}\text{Nb}$ reactions at antiproton-beam energies as shown in the panels. For the Λ and Ξ hyperons also the corresponding yields of them are displayed (dashed curves), which are bound inside the nucleus. The vertical arrows at each panel indicate the rapidity value of the corresponding beam-energy.

detail in previous works [56].

We focus now on the formation of the heavy Ω -hyperon. It can be seen in Fig. 4 that the Ω -production is a very rare process in antiproton-induced reactions at beam energies just close to the Ω -production threshold of $\sqrt{s} \simeq 3.344$ GeV. We emphasize that we have analyzed around 4 millions of transport-theoretical events for each incident energy. The main reason for the low production yields of the Ω -baryon is the extremely low annihilation cross section of several nb only. This value is far below the annihilation cross section of other exclusive processes. The major contribution to the annihilation cross section comes from multiple meson production [98]. It is important to note that the origin of the produced Ω -particles isn't $p\bar{p}$ -annihilation, but other secondary processes involving re-scattering between antikaons, antikaonic resonances with hyperonic resonances ($Y^*(S = -1)$). For instance, for the reaction $\bar{p} + {}^{93}\text{Nb}$ at 4 GeV incident energy these secondary scattering processes contribute with a cross section of 1.148 nb to the total Ω -production yield with a cross section of $\sigma_{\Omega} = 1.15$ nb. The cascade particles and their resonances, which carries already $S = -2$ and thus would preferably contribute to the Ω -formation, mainly escape the target nucleus. For this reason they do not contribute here.

The realization of a second target using the produced cascade particles as a secondary beam is important. At first, for the copious production of multi-strangeness hyperons and multi-strangeness hypernuclei, as proposed by the $\bar{\text{P}}\text{ANDA}$ -experiment [57, 58]. According to the $\bar{\text{P}}\text{ANDA}$ -proposal low-energy Ξ -beams will be used for the production of $\Lambda\Lambda$ -hypernuclei. First theoretical predictions on such exotic hypermatter in low-energy Ξ -induced reactions have been indeed reported in Ref. [56]. Not only $\Lambda\Lambda$ -hypernuclei, but also the direct formation of Ξ -hypermatter is accessible depending on the cascade-nucleon interaction [56].

We show now that the same experiment can be used to explore the formation of Ω -baryons.

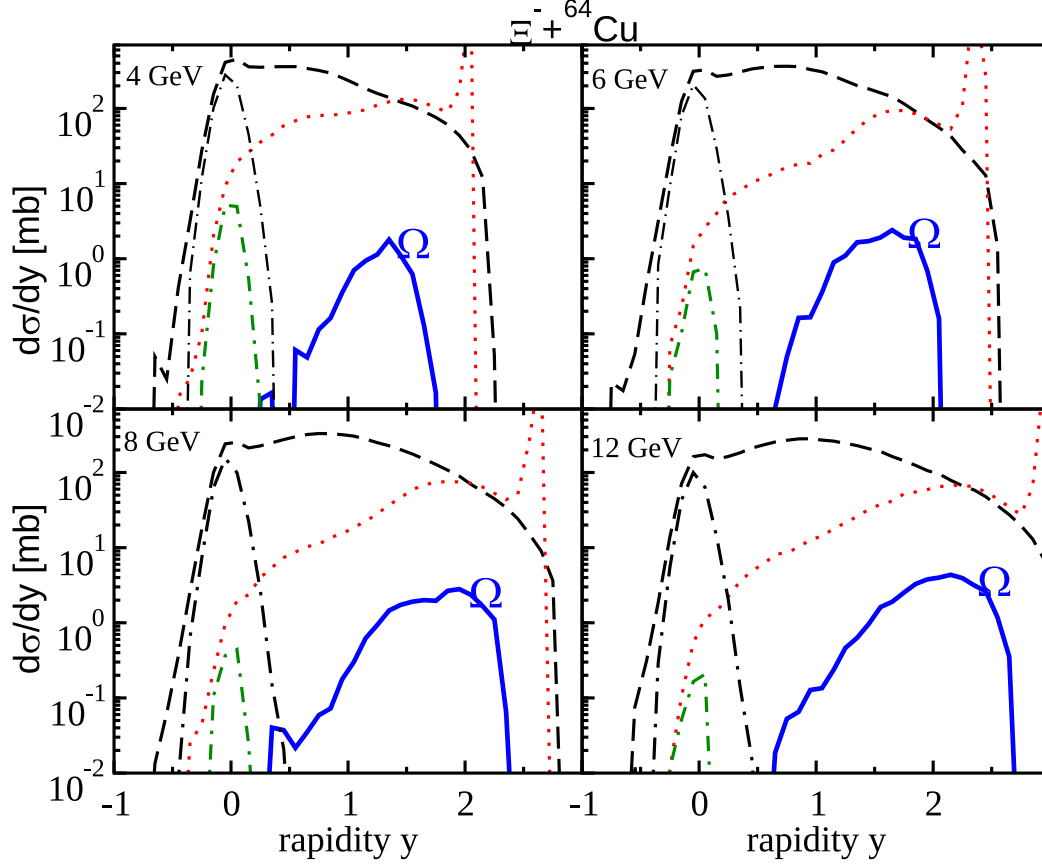


Figure 5: Rapidity distributions of different hyperons for Ξ -induced reactions on ^{64}Cu -targets at four beam-energies, as indicated in each panel. Dotted curve: Ξ^- , dashed curve: Λ^- , dott-dashed curve: bound Λ^- , dot-dot-dashed curve: bound Ξ^- , thick solid curve: Ω^- -rapidity spectra.

This decuplet-hyperon is heavy causing high production thresholds. As discussed above, secondary re-scattering including intermediate production of high-mass hyperonic resonances can be a more favorable possibility for Ω -production. Due to the high strangeness value of this baryon the entrance channel should have as high as possible strangeness degree. Thus, the $\bar{\text{PANDA}}$ -experiment with the secondary Ξ -beam can be a good candidate for our purpose. This is shown in Fig. 5 in terms of the rapidity spectra, but now for Ξ -induced reactions at higher incident energies just above the Ω -production thresholds. At first, similar dynamic effects are observed for the Λ -hyperons as in the \bar{p} -induced reactions. They show the expected broad spectrum in rapidity (dashed curves) due to the enhanced multiple re-scattering. Latter causes also here their abundant capture inside the target nucleus, as shown by the dotted-dashed curves. The rapidity distributions of the cascade particles (dotted curves) are obviously peaked around the beam-value, but there is a significant contribution to lower rapidities too. This feature is again due to the secondary scattering, as discussed in previous works [56]. The production of bound cascade hyperons (dotted-dotted-dashed curves) is now enhanced. This effect induces the formation of exotic Ξ -hypernuclei (for more details on this task see Ref. [56]).

The most interesting part for the present work is the thick-solid curves in Fig. 5, which show the rapidity yields of the produced Ω -baryons. The formation dynamics of the decuplet-particles

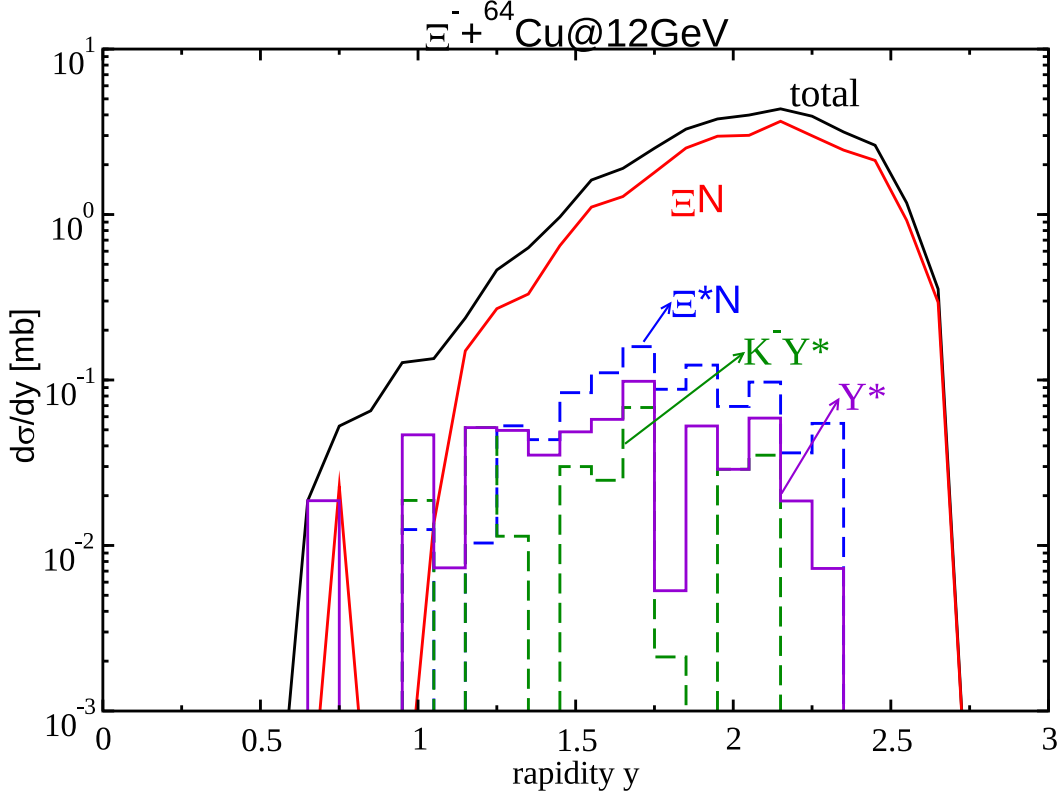


Figure 6: Rapidity distributions for Ω -hyperons in the reaction $\Xi^- + {}^{64}\text{Cu}$ at 12 GeV incident energy. Rapidity spectra for the total Ω -yield (thick-solid black curve) and some particular contributions (thick-solid red: ΞN , dashed blue: $\Xi^* N$, thick-dashed green: $K^- Y^*$, solid-violet: Y^*) to the total spectrum are shown.

here is similar to the dynamical production of the cascade particles in \bar{p} -induced reactions (for comparison see Fig. 4 again). However, the peak of the rapidity spectra of the Ω baryons is now located to much higher energies. In particular, the probability of bound Ω -particles inside the residual nucleus is very low. These different dynamical formations between the Ξ - and Ω -particles have physical reasons beyond the trivial ones (slightly different target masses and beam-energies). The decuplet particles are much heavier and carry one additional strangeness degree of freedom. Latter property causes multi-particle final states in many secondary processes of Ω -production due to strangeness conservation. For instance, in binary collisions between the cascade-beam with other nucleons three final-state particles are required to conserve strangeness and baryon numbers. This leads to rather high threshold energies. The Ω -production thresholds are also high in other secondary processes between the abundantly produced antikaons $K^- (S = -1)$ with hyperons or hyperonic resonances $\Lambda, \Sigma, Y^* (S = -1)$. Thus, the Ω -particles are produced with relatively high energies. The probability of secondary Ω -scattering is low and they escape most likely the nucleus.

Another interesting result is, that the Ω -formation is pronounced largely in Ξ -nucleus collisions relative to the antiproton-induced reactions. In fact, the Ω -production cross sections are in the range between 0.7 – 3.5 mb for the incident Ξ -energies under consideration. This arises from the rather high cross section values of secondary scattering ranging in the mb-region. This is manifested in Fig. 6. It shows the contributions of various channels to the total Ω -yield for the

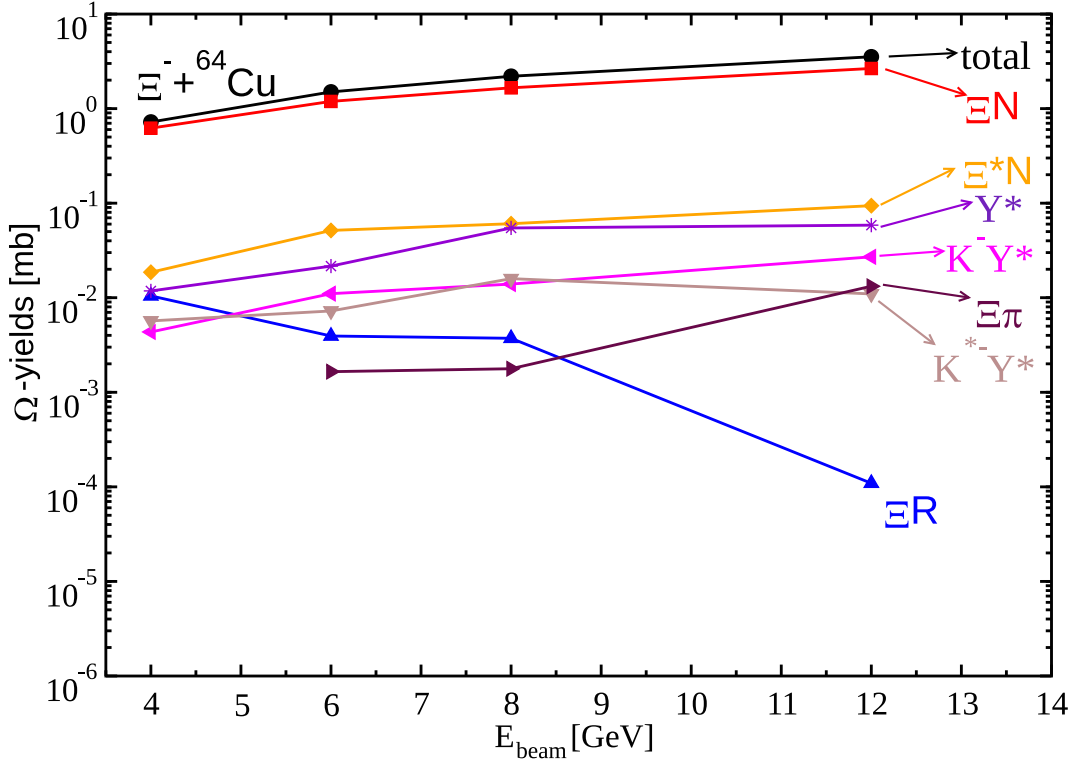


Figure 7: Ω -production yields as function of the incident energy (in units of GeV) for $\Xi^- + {}^{64}\text{Cu}$ -reactions. (circles) total yield, (squares) ΞN -contribution, (diamonds) $\Xi^* N$ -contribution, (stars) Y^* -contribution, (left triangles) $K^- Y^*$ -contribution, (right triangles) $\Xi\pi$ -contribution, (bottom triangles) $K^{*-} Y^*$ -contribution, (top triangles) ΞR -contribution.

$\Xi^- + {}^{64}\text{Cu}$ -reaction at an incident Ξ -energy of 12 GeV. The high momentum part of the produced Ω -particles comes from primary collisions between the Ξ -beam and target nucleons. However, as one can see in Fig. 6, the second-chance collisions involving antikaonic and hyperonic resonances contribute considerably to the Ω -production over a broad longitudinal momentum, even for the intermediate mass number $A = 64$ of the target nucleus.

A more complete picture is given in Fig. 7, where the total Ω -production yield and the most important contributions to it are displayed as function of the incident energy of the secondary cascade beam. The Ξ -nucleon binary collisions dominate over this energy range, as expected. The other secondary processes with the major contribution to the Ω -multiplicity involve scattering between cascade resonances (Ξ^*) with nucleons and scattering between antikaons (K^- , K^{*-}) with hyperonic resonances (Y^*). Furthermore, with increasing beam energy channels with higher-mass resonances open, in particular, those channels with the hyperonic resonances. Therefore, the contributions from ΞR -scattering (with R being non-strange resonances) drops as the energy increases. Finally, the secondary scattering between cascade particles and non-strange mesons ($\Xi\pi$ -channel) opens at higher energies only. In general, secondary processes with a hyperonic resonance Y^* in the initial channel together with the ΞN -collisions mainly contribute to the production of Ω -baryons. We predict total Ω -production yields of several mb in the second-step Ξ -induced reactions and conclude the importance of the $\bar{\text{P}}\text{ANDA}$ -proposal towards the investigation of multi-strange in-medium hadronic interactions. In particular, as pointed out in the pre-

vious Sec. 2, many theoretical models, for instance the chiral EFT calculations, provide us with elastic and quasi-elastic cross sections for scattering processes between the cascade baryon (Ξ) and the lighter Λ - and Σ -hyperons. Due to the importance of these secondary binary collisions to the dynamical formation of Ω -baryons, the Ξ -nucleus reactions of the $\bar{\text{PANDA}}$ -experiment may serve to better constrain the still existing uncertainties in these theoretical approaches.

4. Summary and conclusions

In summary, we have continued our previous investigations on multi-strangeness hypernuclear physics towards the decuplet-sector of SU(3) symmetry by considering the propagation and formation of the heavy Ω -baryon in hadronic reactions relevant for FAIR. That is, antiproton-induced reactions supplemented by a secondary beam of Ξ -particles on an additional nuclear target. The theoretical description of these dynamical processes has been performed within the microscopic transport approach extended by the relevant Ω -production channels, as far as phenomenological information was available.

At first, we have studied the elementary processes leading to the formation of Ω -hyperons. The primary channel consists of $N\bar{N}$ -annihilation into $\Omega\bar{\Omega}$, for which theoretical estimations exist in the literature. The predicted $N\bar{N} \rightarrow \Omega\bar{\Omega}$ -cross sections are too small with respect to other annihilation processes. In particular, the Ω -production cross sections take values of a few nb only, which is approximately six orders of magnitude less than the nucleon-antinucleon annihilation into mesons. On the other hand, secondary re-scattering between antikaons and strangeness resonances occurs with much higher probability in the mb-regime.

In \bar{p} -nucleus reactions the formation probability of Ω -particles is a very rare process. For this type of reactions we estimate Ω -production yields of a few nb only. It turns out that secondary processes only do create Ω -hyperons with a vanishing contribution from the primary $N\bar{N} \rightarrow \Omega\bar{\Omega}$.

Our calculations, however, support the two-step reaction mechanism at $\bar{\text{PANDA}}$ for the observation of Ω -hyperons. To be more precise, using the produced cascade-particles of the first-step \bar{p} -nucleus collisions as a secondary beam, additional transport calculations for the realization of Ξ -induced reactions were performed. A high energy Ξ -beam was utilized to overcome the high Ω -production thresholds. At first, an abundant production of the lighter Λ - and Ξ -hyperons was observed in consistency with previous studies. The most important result was the formation of the Ω -particles in Ξ -nucleus collisions with an observable probability. It is still an open question how the Ω^- -hyperon can be observed experimentally probably by requiring reconstruction from coincidence experiments and particle correlations. However, the production cross sections in the mb-region, as estimated from the present analysis, indicate a high production rate. The dynamical formation of these heavy hyperons was investigated too. For multiple Ω -formation the ΞN -processes gives the highest contribution, as expected for these reactions with the Ξ -beam. As an interesting feature the contributions from other secondary channels was significant even with a intermediate-mass target nucleus. It would be a challenge to explore such dynamical hadron-nucleus reactions experimentally too. It will be important to constraint better the physical picture of multi-strangeness elementary processes.

We conclude with pointing out the great opportunity of the future activities at FAIR to understand deeper the still little known high strangeness sector of the hadronic equation of state.

Note that the strangeness sector of the baryonic equation of state is crucial for our knowledge in nuclear and hadron physics and astrophysics. For instance, hyperons in nuclei do not experience Pauli blocking within the Fermi-sea of nucleons. Thus they are well suited for explorations of single-particle dynamics. In highly compressed matter in neutron stars the formation of particles with strangeness degree of freedom is energetically allowed. Of particular interest are hereby the Λ -, Σ -, Ξ - and Ω -hyperons with strangeness $S=-1, -2$ and -3 , respectively. As shown in recent studies [4, 99], these hyperons modify the stiffness of the baryonic EoS at high densities considerably leading to the puzzling disagreement with recent observations of neutron stars in the range of 2 solar masses.

Acknowledgement

Supported in part by DFG, contract Le439/9, BMBF, contract 05P12RGFTE, GSI Darmstadt, and Helmholtz International Center for FAIR.

References

References

- [1] I. Sagert, *et al.*, Phys. Rev. Lett. 102 (2009) 081101.
- [2] S. Weissenborn, D. Chatterjee, J. Schaffner-Bielich, Nucl. Phys. A914 (2013) 421;
S. Weissenborn, D. Chatterjee, J. Schaffner-Bielich, Phys.Rev. C85 (2012) 065802,
Phys.Rev. C90 (2014) 019904.
- [3] J. Schaffner-Bielich, A. Gal, Phys. Rev. C62 (2000) 034311.
- [4] J. Schaffner-Bielich, I.N. Mishustin, Phys. Rev. C53 (1996) 1416.
- [5] O. Hashimoto, H. Tamura, Prog. Part. Nucl. Phys. 57 (2006) 564.
- [6] M. Fortin, J.L. Zdunik, P. Haensel, M. Bejger, Astron. Astrophys. A68 (2015) 576.
- [7] S. Banik, M. Hempel, D. Bandyopadhyay, Astrophys. J. Suppl. 214 (2014) 22.
- [8] M. Prakash, I. Bombaci, M. Prakash, P. J. Ellis, J. M. Lattimer and R. Knorren, Phys. Rept. 280 (1997) 1.
- [9] P. Demorest, T. Pennucci, S. Ransom, M. Roberts and J. Hessels, Nature 467 (2010) 1081.
- [10] J. Antoniadis *et al.*, Science 340 (2013) 6131.
- [11] I. Bombaci, arXiv: 1601.05339 [nucl-th];
T. Katayama and K. Saito, arXiv:1410.7166 [nucl-th];
H. J. Schulze, Prog. Theor. Phys. Suppl. 186 (2010) 57.

- [12] I. Vidana, A. Polls, A. Ramos, M. Hjorth-Jensen and V. G. J. Stoks, Phys. Rev. C61 (2000) 025802.
- [13] I. Vidana, A. Polls, A. Ramos, L. Engvik and M. Hjorth-Jensen, Phys. Rev. C62 (2000) 035801.
- [14] K. A. Maslov, E. E. Kolomeitsev and D. N. Voskresensky, Phys. Lett. B748 (2015) 369.
- [15] A. Ohnishi, K. Tsubakihara, K. Sumiyoshi, C. Ishizuka, S. Yamada and H. Suzuki, Nucl. Phys. A835 (2010) 374.
- [16] Y. Lim, C. H. Hyun, K. Kwak and C. H. Lee, Int. J. Mod. Phys. E24 (2015) 12, 1550100.
- [17] D. Chatterjee and I. Vidana, Eur. Phys. J. A52 (2016) 29.
- [18] D. Blaschke and D. E. Alvarez-Castillo, AIP Conf. Proc. 1701 (2016) 020013.
- [19] D. Lonardoni, A. Lovato, S. Gandolfi and F. Pederiva, Phys. Rev. Lett. 114 (2015) 9, 092301.
- [20] D. G. Yakovlev and C. J. Pethick, Ann. Rev. Astron. Astrophys. 42 (2004) 169.
- [21] N.K. Glendenning, *Compact Stars: Nuclear Physics, Particle Physics, and General Relativity*, (Springer, Berlin, 2000).
- [22] F. Weber, *Pulsars as Astrophysical Laboratories for Nuclear and Particle Physics*, IOP Publishing, Bristol, Philadelphia, 1999.
- [23] J. M. Lattimer, EPJ Web Conf. 109 (2016) 07001.
- [24] J. M. Lattimer and M. Prakash, Phys. Rept. 621 (2016) 127.
- [25] W. Reisdorf and H. G. Ritter, Ann. Rev. Nucl. Part. Sci. 47 (1997) 663.
- [26] N. Herrmann, J.P. Wessels, T. Wienold, Annu. Rev. Nucl. Part. Sci. 49 (1999) 581.
- [27] C. Fuchs, Prog. Part. Nucl. Phys. 56 (2006) 1.
- [28] C. Hartnack, H. Oeschler, Y. Leifels, E. L. Bratkovskaya and J. Aichelin, Phys. Rept. 510 (2012) 119.
- [29] A. Forster *et al.*, Phys. Rev. C75 (2007) 024906.
- [30] W. Cassing, L. Tolos, E. L. Bratkovskaya and A. Ramos, Nucl. Phys. A727 (2003) 59.
- [31] W. Cassing and E. L. Bratkovskaya, Phys. Rept. 308 (1999) 65.
- [32] P. Danielewicz, R. Lacey and W. G. Lynch, Science 298 (2002) 1592.
- [33] M. B. Tsang *et al.*, Phys. Rev. C86 (2012) 015803.

- [34] A. L. Watts *et al.*, arXiv:1602.01081 [astro-ph.HE].
- [35] G. Agakishiev *et al.* [HADES Collaboration], Phys. Rev. C90 (2014) 054906.
- [36] B. Tomasik, E.E. Kolomeitsev, J. Phys. Conf. Ser. 668 (2016) 1, 012089.
- [37] C. Rappold, T.R. Saito, O. Bertini, *et al.*, Phys. Lett. B747 (2015) 129.
- [38] A.S. Lorente, S. Bleser, M. Steinen, J. Pochodzalla, Phys. Lett. B749 (2015) 421.
- [39] A.S. Botvina, J. Steinheimer, E. Bratkovskaya, M. Bleicher, J. Pochodzalla, Phys. Lett. B742 (2015) 7.
- [40] J. Haidenbauer, U.-G. Meissner, A. Nogga, H. Polinder, Lect. Notes Phys. 724 (2007) 113.
- [41] E. Friedmann, A. Gal, Phys. Rep. 452 (2007) 89.
- [42] B. F. Gibson and E. V. Hungerford, Phys. Rept. 257 (1995) 349.
- [43] A.D. Wroblewski, Acta Physica Polonica B35 (2004) 901.
- [44] J. Schaffner-Bielich, Nucl. Phys. A804 (2008) 309.
- [45] K.A. Olive, *et al.* (Particle Data Group), Chin. Phys. C38 (2014) 090001.
- [46] B. Holzenkamp, K. Holinde, J. Speth, Nucl. Phys. A500 (1989) 485;
A. Reuber, K. Holinde, J. Speth, Nucl. Phys. A570 (1994) 543.
- [47] Y. Fujiwara, C. Nakamoto, Y. Suzuki, Phys. Rev. 54 (1996) 2180;
M. Kohno, *et al.*, Nucl. Phys. A674 (2000) 229;
Y. Fujiwara, Y. Suzuki, C. Nakamoto, Prog. Part. Nucl. Phys. 58 (2007) 439.
- [48] A. Valcarce, *et al.*, Rept. Prog. Phys. 68 (2005) 965.
- [49] Th.A. Rijken, V.G.J. Stoks, Y. Yamamoto, Phys. Rev. 59 (1999) 21;
Th.A. Rijken, Phys. Rev. C73 (2006) 044007;
Th.A. Rijken, Y. Yamamoto, Phys. Rev. C73 (2006) 044008 (2006).
- [50] K. Sasaki, E. Oset, and M. J. Vicente Vacas, Phys. Rev. C74 (2006) 064002;
J. Haidenbauer, U.-G. Meissner, Phys. Rev. C72 (2005) 044005.
- [51] J.K. Ahn, *et al.*, Phys. Lett. B633 (2006) 214.
- [52] A. B. Larionov, T. Gaitanos and U. Mosel, Phys. Rev. C85 (2012) 024614.
- [53] T. Gaitanos, H. Lenske and U. Mosel, Phys. Lett. B663 (2008) 197.
- [54] T. Gaitanos, *et al.*, Nucl. Phys. A914 (2013) 405.
- [55] T. Gaitanos, H. Lenske and U. Mosel, Phys. Lett. B675 (2009) 297.

- [56] T. Gaitanos and H. Lenske, Phys. Lett. B737 (2014) 256.
- [57] M. F. M. Lutz, *et al.*, [PANDA Collaboration], arXiv:0903.3905 [hep-ex].
- [58] A. Esser, *et al.*, Nucl. Phys. A914 (2013) 519.
- [59] O. Hashimoto, *et al.*, Nucl.Phys. A835 (2010) 121
- [60] A.K. Kerman, *et al.* Phys.Rev. C8 (1973) 408.
- [61] Z. Rudy et al., Z. Phys. A351 (1995) 217.
- [62] J. Aichelin, K. Werner, Phys. Lett. B274 (1992) 260.
- [63] M. Wakai, Nucl. Phys. A547 (1992) 89c.
- [64] STAR Collaboration, Science 328 (2010) 58.
- [65] J. Pochodzalla, Acta Phys. Polon. B42 (2011) 833.
- [66] C. Rappold, T. R. Saito, S. Bianchin, O. Borodina, *et al.*, Nucl. Instrum. Meth. A622 (2010) 231.
- [67] T. R. Saito, S. Bianchin, O. Borodina, J. Hoffmann, *et al.*, Int. J. Mod. Phys. E19 (2010) 2656.
- [68] GSI Scientific report, PHN-NQM-FOPI-03.
- [69] J. Steinheimer, *et al.*, J. Phys. Conf. Ser. 389 (2012) 012022.
- [70] A.S. Botvina, *et al.*, Nucl. Phys. A881 (2012) 228.
- [71] A.S. Botvina and J. Pochodzalla, Phys. Rev. C76 (2007) 024909.
- [72] Th.A. Rijken, V.G.J. Stoks, Y. Yamamoto, Phys. Rev. C59 (1999) 21;
Th.A. Rijken, Phys. Rev. C73 (2006) 044007;
Th.A. Rijken, Y. Yamamoto, Phys. Rev. C73 044008 (2006).
- [73] Y. Yamamoto, T. Furumoto, N. Yasutake, and Th. A. Rijken, Phys. Rev. C90 (2014) 045805.
- [74] J. Haidenbauer, U.-G. Meissner, A. Nogga, H. Polinder, Lect. Notes Phys. 724 (2007) 113;
B. Holzenkamp, K. Holinde, J. Speth, Nucl. Phys. A500 (1989) 485;
A. Reuber, K. Holinde, J. Speth, Nucl. Phys. A570 (1994) 543.
- [75] M. Kohno, Y. Fujiwara, Phys. Rev. C79 (2009) 054318.
- [76] H. Lenske, M. Dhar, T. Gaitanos, arXiv:1602.08917 [nucl-th].
- [77] G. Alexander, U. Karshon, A. Shapira, G. Yekutieli, R. Engelmann, H. Filthuth, and W. Lughofer, Phys. Rev. 173 (1968) 1452.

- [78] B. Sechi-Zorn, B. Kehoe, J. Twitty, and R.A. Burnstein, Phys. Rev. 175 (1968) 1735.
- [79] F. Eisele, H. Filthuth, W. Fölisch, V. Hepp, E. Leitner, and G. Zech, Phys. Lett. B37B (1971) 204.
- [80] B. Borasoy, E. Epelbaum, H. Krebs, D. Lee, and U.-G. Meissner, Eur. Phys. J. A31 (2007) 105;
E. Epelbaum, H. Krebs, D. Lee, and U.-G. Meissner, Phys. Rev. Lett. 106 (2011) 192501;
U.-G. Meissner, Nucl. Phys. News 24 (2014) 11.
- [81] E. Epelbaum, W. Glöckle, U.-G. Meissner, Nucl. Phys. A747 (2005) 362.
- [82] H. Polinder, J. Haidenbauer and U. G. Meissner, Nucl. Phys. A779 (2006) 244.
- [83] J. Haidenbauer, S. Petschauer, N. Kaiser, U.-G. Meissner, A. Nogga and W. Weise, Nucl. Phys. A915 (2013) 24.
- [84] S. Petschauer, J. Haidenbauer, N. Kaiser, U. G. Meissner and W. Weise, Eur. Phys. J. A52 (2016) 15.
- [85] J. Haidenbauer and U.-G. Meissner, Phys. Lett. B684 (2010) 275.
- [86] J. Haidenbauer, U. G. Meiner and S. Petschauer, arXiv:1511.05859 [nucl-th].
- [87] Y. Fujiwara, *et al.*, Phys. Rev. C64 (2001) 054001.
- [88] A.B. Kaidalov, P.E. Volkovitsky, Z. Phys. C63 (1994) 517.
- [89] T. Sjostrand, S. Mrenna and P. Z. Skands, JHEP 0605 (2006) 026, [hep-ph/0603175].
- [90] W. Botermans and R. Malfliet, Phys. Rept. 198 (1990) 115.
- [91] O. Buss, *et al.*, Phys. Rept. 512 (2012) 1.
- [92] H.-P. Duerr, Phys. Rev. 103 (1956) 469;
J. Walecka, Annals Phys. 83 (1974) 491;
B. D. Serot and J. D. Walecka, Int. J. Mod. Phys. E6 (1997) 515.
- [93] G.A. Lalazissis, *et al.*, Phys. Lett. B671 (2009) 36.
- [94] Landolt-Börnstein, New Series I/12b, [http : //dx.doi.org/10.1007/b35211](http://dx.doi.org/10.1007/b35211).
- [95] T.A. Rijken, Y. Yamamoto, nucl-th/0608074.
- [96] T. Gaitanos, M. Kaskulov, Nucl. Phys. A940 (2015) 181.
- [97] E. Friedman, A. Gal, J. Mares, Nucl. Phys. A761 (2005) 283.
- [98] E.S. Golubeva, A.S. Iljinov, B.V. Krippa, I.A. Pshenichnov, Nucl. Phys. A537 (1992) 393.
- [99] S. Weissenborn, D. Chatterjee and J. Schaffner-Bielich, Nucl. Phys. A881 (2012) 62.